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sdO and peculiar X-ray emissions

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Abstract

Some Be stars exhibit a bright and extremely hard X-ray emission, whose origin is debated. In this context, it has been advocated that stripped helium-star sdO companions could play a significant role. Using high quality datasets, we examined (1) the binarity of these peculiar Be stars and (2) the X-ray emission of known Be+sdO systems. In this contribution, we present the result of these two studies and assess their impact on the proposed scenario.

Keywords: stars: early-type – stars: massive – stars: emission-line, Be – binaries: general – X-rays: stars

Résumé

Les étoiles sdO et les émissions en rayons X particulières Certaines étoiles de type Be présentent une émission en rayons X brillante et très dure, d'origine débattue. Il a notamment été proposé que des compagnons sdO pouvaient jouent un rôle majeur dans la génération de cette émission. Grâce à des donnés inédites de grande qualité, nous avons étudié (1) la binarité de ces étoiles Be particulières et (2) l'émission en rayons X de systèmes Be+sdO. Cette contribution présente les résultats de ces deux recherches et leur impact sur le scénario proposé.

Mots-clés : étoiles: type précoce – étoiles: massives – étoiles: Be – binaires – rayons X: étoiles

1. Introduction

In the 19th century, γ Cas was the first star detected to have Balmer lines in emission in its spectrum (Secchi, 1866). This led to the definition of the Be spectral class. The star remained the class prototype for about a century, when it was finally found that its X-ray emission was strikingly different from the one recorded for other massive OB stars (Jernigan, 1976).

To understand how peculiar this emission is, it is of interest to recall what a “normal” emission should look like (for a review, see Rauw 2022). The intrinsic X-ray emission of massive OB stars is in fact linked to their strong stellar winds. Those winds are line-driven but this process is unstable. Parts of such winds are thus flowing at different velocities and therefore collide, generating hot plasma. This hot plasma then emits X-rays corresponding to optically-thin thermal emission. The resulting plasma temperature is relatively low (0.2–0.6 keV) and, since the wind acceleration is ultimately due to the intense UV radiation, the total X-ray luminosity appears strongly correlated to the bolometric luminosity ($\log[L_{\rm X}/L_{\rm BOL}] \sim -7$). In addition, the X-ray emission has a stable level because the wind parcels are numerous. Only limited variations of those soft X-rays may occur in some cases, due to the presence of large-scale wind structures. Indeed, X-ray modulations linked to pulsations or wind co-rotating interaction regions have been observed in a few cases.

If a massive star is strongly magnetic, its wind flows will follow the magnetic field lines and collide at the equator. If two massive stars form a binary, then their two stellar winds may collide, which sometimes leads to the generation of hotter plasma. Such collisions then constitute additional sources of X-rays and, as a consequence, the X-ray luminosity will be larger, although by no more than one dex generally. In addition, since those collisions occur face-on, they often generate hotter plasma, hence harder X-rays. The plasma temperature may then reach a few keV. A last characteristic of those emissions are X-ray variations recurring with the rotation period for magnetically confined winds or with the orbital period for colliding wind binaries.

In contrast, γ Cas displays an optically thin thermal emission associated with a temperature of 13 keV and its X-ray to bolometric luminosity ratio reaches $\log[L_{\rm X}/L_{\rm BOL}] \sim -5.4$. Moreover, its X-ray emission varies on several timescales, with “shots” down to a few seconds duration, $\sim$70 d cycles, and long-term changes. None of these timescales appears related to its rotational period or to its orbital period (Smith et al., 2016; Rauw et al., 2022). In the last two decades, other stars were found to display similar X-ray characteristics. Formal criteria for a γ Cas classification are: $\log[L_{\rm X}/L_{\rm BOL}]$ between –6.2 and –4.0, and $kT > 5$ keV (Nazé et al., 2020). Two dozen of such objects are now known and they are then collectively called “γ Cas analogs” or “γ Cas stars” (note that this is unrelated to the old/outdated GCAS photometric classification in the optical[1]). In this context, it is important to note that all γ Cas stars identified up to now are Be stars, but clearly not all Be stars display the γ Cas character in the high-energy range.

The origin of this hard and bright X-ray emission has been debated, with several scenarios proposed by different authors. The scenarios can be split in two broad families. The first one considers the Be star as the main responsible for the X-rays (Motch et al., 2015). Fast-rotating stars may have subsurface convection zones from which small-scale magnetic fields can arise. In addition, instabilities in the disk may lead to the generation of small-scale magnetism in the disk. If magnetic reconnection events occur, it could lead to bright and hard X-ray emission. The second family of scenarios rather links the X-ray emission to a companion of the Be star. Accretion onto a compact companion (white dwarf, neutron star) has been proposed, although

[1] http://www.sai.msu.su/gcvs/gcvs/vartype.htm

unusual configurations may be needed (e.g. propeller stage for an accreting neutron star, see Postnov et al. 2017). As an alternative, a collision between the Be disk and the wind of a hot, stripped star companion was also advanced as a possibility to produce the observed X-rays (Langer et al., 2020).

The presence of companions of Be stars is not unexpected. Indeed, binarity is at the heart of one of the most popular evolutionary channels explaining the origin of Be stars. In this scenario, the companion of the Be star was initially the most massive object. As it evolved, it began to interact with the lower mass star of the system. The mass transfer increased the mass of this object but also accelerated its rotation, which ultimately led to the birth of a fast-rotating Be star. The companion, now stripped of its envelope, becomes either a white dwarf or a sdO helium star - much more rarely, according to models, the companion is a neutron star or a black hole (Shao and Li, 2014). The preponderance of binary interactions in the formation of Be stars is supported by several pieces of observational evidence. Amongst them are the absence of main-sequence companions while other OB stars are often paired with similar objects (Bodensteiner et al., 2020), the presence of companions needed to get truncated disks as indicated by SED fitting (Klement et al., 2019), or the fraction of runaways amongst Be stars in line with population synthesis predictions (Boubert and Evans, 2018). Also, UV spectroscopy provided the direct signature of sdO companions for 18 Be stars (Wang et al., 2021).

Therefore, the colliding wind-disk scenario should be thoroughly tested. To this aim, we acquired specific data which enabled us to investigate the multiplicity of γ Cas objects (Nazé et al., 2022b) and the X-ray emission of Be+sdO systems (Nazé et al., 2022c). We now summarize the findings reported in those two papers.

2. Are γ Cas stars binaries?

Amongst γ Cas analogs, two have been known to be binaries for decades: γ Cas (Harmanec et al., 2000) and π Aqr (Bjorkman et al., 2002). The others had not been throughly investigated, and so we decided to perform a specific spectroscopic monitoring (Nazé et al., 2022b) using high-resolution spectrographs installed on TIGRE (Mexico), VLT (Chile), and Calar Alto 3.5m telescope (Spain). The targets are 16 γ Cas analogs known at that time - a few additional objects could not be monitored due to their faintness. Amongst the investigated sample, five stars show velocity changes typical of binary motion, but the small number of spectra did not allow us to derive a full orbital solution. For six other stars, orbital solutions could be derived. One of the systems is actually quadruple: V782 Cas appears to be composed of a Be binary and an eclipsing binary. The remaining targets did not lead to clear binary signatures as they often display strongly variable disks which blurred the velocity determination.

All orbital solutions present similarities: low velocity amplitudes and rather long periods (months). This implies a low mass for the companions (0.5–2 $M_\odot$) and not-so-small (about 1 AU, or tens of R_*) separations. Prime candidates for these companions are thus stripped stars. However, when compared to other known spectroscopic Be binaries, the γ Cas binaries do not show specific orbital/stellar properties. Therefore, while the γ Cas analogs may well correspond to Be+sdO systems, this multiplicity does not seem to be the culprit for their X-ray peculiarities.

3. Are Be+sdO peculiar X-ray emitters?

While many Be stars have been identified in the Galaxy (the BeSS database[2] contains more than 1500 cases), only a small fraction has been the target of X-ray observations. In this context, we have analyzed Chandra, XMM, and Swift observations of a specific sample. It consists of 18 Be+sdO systems (Wang et al., 2021) and seven Be spectroscopic binaries for which the low-mass companion could be a stripped, subdwarf star. Amongst these 25 targets, there were 9 detections, seven with X-rays confined to the low-energy range and two showing a bright and hard emission, typical of γ Cas stars.

X-ray luminosities, or upper limits on the luminosities, were derived using either the recorded spectral characteristics or the count rates. The derived values show that two systems had γ Cas characteristics; one was known before. Two other systems have so high upper limits that nothing can really be concluded on their nature. The rest of the targets appear clearly below the γ Cas threshold, most with $\log[L_X/L_{BOL}] < -7$. The low incidence rate of the γ Cas phenomenon observed in this sample is similar to that recorded in other Be samples (Nazé and Motch, 2018; Nazé et al., 2020, 2022c). In addition, there is no evidence of any correlation with the subdwarf properties (mass, temperature, luminosity) or the orbital properties (separation/period). This is at odds with expectations of the colliding wind-disk scenario.

4. Conclusion

Some Be stars, among which is the famous prototype γ Cas, display bright and hard X-rays at odds with the high-energy emissions observed in other OB stars. One proposed scenario explains these peculiarities by a collision between the Be disk and the stellar wind of its hot, stripped star companion. Thanks to new spectroscopic monitoring, we show that γ Cas analogs often form a binary system with a low-mass companion. However, the multiplicity properties appear in agreement with what is observed for other Be stars. Additional X-ray observations also enable us to study known Be+sdO systems or candidates. Only two of them display the γ Cas character, in line with the incidence rate observed in other Be samples. In addition, (1) modulation of the X-ray flux with orbital phase, typical of colliding winds, is not recorded for the intensively monitored γ Cas systems (Nazé et al., 2019; Rauw et al., 2022) and (2) simultaneous X-ray/optical monitoring indicates that the γ Cas character may remain even if the Be disk is very small, which favors an X-ray source close to the star (Nazé et al., 2022a). All this suggests that the companion, probably sdO-type, plays little role in the generation of the peculiar X-rays.

[2] http://basebe.obspm.fr/basebe/ (Neiner et al., 2011)

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Further Information

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Author contributions

All authors contributed to the writing of proposals to acquire data on which this paper is based. Y.N. reduced and analyzed the data, using tools and advices from the team, and then prepared the draft. All authors have discussed the results and edited the draft to finalize the version.

Conflicts of interest

The authors declare no conflict of interest.

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